Different Types of X-ray Variability Observed in Micro-Quasar GRS 1915+105 with the IXAE

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Abstract

The galactic micro-quasar source GRS 1915+105 has been observed with the Indian X-ray Astronomy Experiment (IXAE) several times over a period extending from 1996 to 2000. The source has been observed in different luminosity states and exhibits a rich variety of random and regular X-ray variability over a wide range of time scales. It also shows a unique variability characteristic namely the occurrence of quasi-regular X-ray bursts with period ranging from 20 s to about 100 s which have slow rise and fast decay. The X-ray spectrum of these bursts is hardest near the end of decay. In the low-hard state and bright-soft state with rapid variability, the source exhibits quasi-periodic oscillations (QPOs) with variable frequency which is luminosity dependent. Regular X-ray intensity dips have been detected coincident with the occurrence of a giant radio outburst. The source made a transition from a low-state to a high-state in 1999 in less than a day and from a soft-bright state to a hard-low state in 2000 in less than 100 minutes during the IXAE observations. Details of these and other variability characteristics of the source are presented in this paper.

Key words: accretion: accretion disks - black hole physics - X-rays: stars - stars: individual - GRS 1915+105

INTRODUCTION

The galactic X-ray source GRS 1915+105 discovered in 1992 shows superluminal motion and other radio characteristics similar to those of quasars and hence has been termed as a 'micro-quasar'. From resemblance of its spectral and temporal properties with that of superluminal Galactic radio source GRO J1655-40 (Zhang et al. 1997), GRS 1915+105 is believed to be a black hole. The source is very bright in X-ray, emitting at a luminosity of more than 10^{39} erg s⁻¹. It exhibits strong variability over a wide range of time scales in X-ray, infrared and radio bands. The X-ray emission is characterized by chaotic variability as well as narrow quasi-periodic oscillations (QPOs) at centroid frequency in the range of 0.001 - 67 Hz. It is found that the intensity dependent narrow QPOs are a characteristic property of the hard-state which is absent in the soft-state. Based on extensive X-ray studies the behaviour of the source can be classified in two distinct states: the spectrally hard-state, dominated by a power-law component when the QPOs are present and the soft-state, dominated by thermal emission when the QPOs are absent.

The micro-quasar GRS 1915+105 shows a variety of features in the X-ray light curve. Large, eclipse-like dips

in the X-ray flux, called as brightness sputters, with a recurrence time of about 250 s, extremely large amplitude oscillations with an amplitude of ~ 3 Crab and recurrence periods of 30-100 s, fast oscillations in the X-ray flux, brief flares (lasting for a few seconds) following the low level X-ray flux (lull) and several complex type of regular and quasi-regular variations in the X-ray flux are observed in the light curves at different times. Wide range of transient activity, including the regular and quasi-regular bursts with a secondary (and tertiary) weaker burst following the primary burst, are described as a result of thermal instability in the inner accretion disk producing short duration luminosity fluctuations which are observed as bursts. Belloni et al. (2000) have made an extensive study on the X-ray emission of the source and classified all the publicly available RXTE/PCA observations from 1996 January to 1997 December into 12 different classes on the basis of structure of the X-ray light curve and the nature of the color diagram. From the above study, they found that the source variability is restricted into three basic states, a hard-state with non-observability of the inner accretion disk and two soft-states with visible inner accretion disk and at different temperatures depending on the different

Table 1. X-ray Observations of GRS 1915+105 with the IXAE

Year	Observation		Useful	Main X-ray variability Characteristics
of Obs.	start	End	time(s)	
1996	July 20	July 29	8,850	Strong erratic intensity variations on time scale of 0.1–10 s and QPOs in a frequency range of 0.62–0.82 Hz are observed (Paul et al. 1997). The intensity variations are described as sum of shots in the light curve (Paul et al. 1998a).
1997	June 12	June 29	39,300	Different types of intense, quasi-regular X-ray bursts are observed with slow-rise and fast decay and interpreted as the disappearance of matter through event horizon of the black hole (Paul et al. 1998b).
1997	August 07	August 10	20,700	Classification of quasi-regular and irregular X-ray bursts into different classes and explained as the appearance and disappearance of the advective disk over its viscous timescale (Yadav et al. 1999).
1999	June 06	June 17	37,740	Transition from a low-hard state to high-soft state is observed. Detection of a series of soft X-ray dips which are explained as the cause for mass ejection due to the evacuation of matter from an accretion disk producing a huge radio jet in GRS 1915+105 (Naik et al. 2001a).
2000	June 18	June 27	29, 460	Transition from a high-state with regular and periodic bursts with slow rise and sharp decay (class ρ) to a low-hard state is observed within 1.5 hrs (Naik et al. 2001b).

values of mass accretion rate.

Attempts have been made to explain the observed Xray properties of the source with the properties at longer wavelengths. Simultaneous observations at shorter and longer wavelengths have established the correlation between the X-ray variability and the emission at radio and infrared wavelengths (Fender et al. 1999 and reference therein). They showed that the emission at longer wavelengths is associated with the plasma ejection from the instabilities in the inner accretion disk. Naik & Rao (2000) examined the radio properties of the source during all the 12 different X-ray classes. They showed that the huge radio flares are associated with the soft-dips in X-ray light curve (classes θ and β) where as the higher flux density at radio wavelengths with flat spectrum is associated with the X-ray low-hard states referred as "plateau" state (classes $\chi 1$ and $\chi 3$). It is found that in all the other X-ray classes of Belloni et al. (2000) classification, the source remains in a radio-quiet state.

In this paper, we present a summary of the main variability characteristics of the source observed in different states with the Pointed mode Proportional Counters

(PPCs) of IXAE. It was found to be in different brightness states during the five different epochs of observations.

OBSERVATIONS

The X-ray observations of GRS 1915+105 were carried out from 1996 July to 2000 June at five different epochs with the PPCs of the IXAE on board the Indian satellite IRS-P3. The IXAE includes three co-aligned and identical, multi-wire, multi-layer proportional counters, filled with a gas mixture of 90% Argon and 10% Methane at a pressure of 800 torr, with a total effective area of 1200 cm², covering 2 to 18 keV energy range with an average detection efficiency of about 60% at 6 keV. For a detailed description of the PPCs refer to Agrawal (1998). A log of the observations of the source GRS 1915+105 from 1996 July to 2000 June is given in the Table. 1 with the useful period of observations at each epoch and important results obtained in each observation.

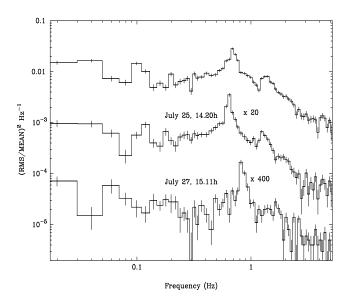


Fig. 1. The Power density spectra of the X-ray source GRS1915+105 observed with IXAE in 2–18 keV energy band. A strong peak at a frequency of 0.7 Hz is clearly visible. The two top plots show power density spectra with peaks at frequencies 0.62 Hz and 0.82 Hz respectively indicating variation of the QPO peak frequency. The dates of observations are given in the figure. The first harmonic at a frequency of twice that of the main peak is seen in all the three plots.

3. RESULTS

Following are the main results obtained from the IXAE observations of GRS 1915+105 from 1996 to 2000.

(i) Intense and erratic intensity variations, including sub-second flares, on time scales of 0.1 s - 1 s were observed in the energy range of 2-18 keV during 1996 July observations of the source. Strong and narrow QPOs in a frequency range of 0.62 - 0.82 Hz with a rms fraction of about 9% were also detected as shown in Figures 1. Besides the low frequency QPOs (0.62 - 0.82 Hz), a less prominent peak at ~ 1.4 Hz which is the first harmonic of the main peak was also detected with the PPCs. The erratic intensity variations on sub-second time scale, low frequency QPOs and super-Eddington luminosity, which are also observed in other stellar black hole X-ray binaries, support the hypothesis that the compact object is most likely a black hole (Paul et al. 1997). Time lag of of 0.2 to 0.4 s of hard X-ray (6-18 keV) photons relative to that of the soft (2-6 keV) photons was also detected which supports the idea of the generation of hard X-ray photons by Compton up-scattering from the high energy clouds near the source of soft X-rays. The observed intensity variations in the light curves are described by a shot noise model (Paul et al. 1998a). Chaotic variability in the intensity is explained as resulting from randomly occurring shots with exponential rise and/or decay.

(ii) Different kinds of periodic and quasi-periodic bursts are observed with the PPCs during different

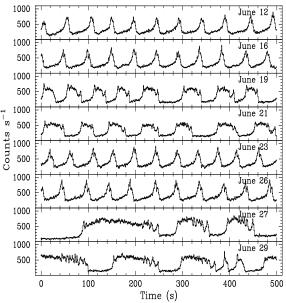


Fig. 2. The regular (first, second, fifth, and sixth panels from the top), irregular (third and fourth panels), and long (seventh and eighth panels) bursts observed in GRS 1915+105 with one of the PPCs in June 1997 as indicated in the respective panels.

epochs. These bursts are classified into four different classes on the basis of the different time scales such as (1) regular bursts having a slow rise and fast decay lasting for ~ 15 s and recurring every 21 s; (2) regular bursts, having a slow rise and sharp decay lasting for ~ 20 s and recurring every 46 s; (3) quasi-regular bursts of variable duration with slow rise and sharp decay; and (4) irregular bursts, with duration of a few tens to a few hundreds of seconds, followed by sharp decay. Figure 2 shows the structures of different types of regular and quasi-regular bursts, which were detected from the 1997 June observations of the source. These bursts are characterized by an exponential rise with a timescale of about 7-10 s and a sharp linear decay in 2-3 s. The slow rise time of the bursts is explained as the infall time of matter from the accretion disk and the fast decay is due to the disappearance of matter through the event horizon of the black hole (Paul et al. 1998b). The repetition of these regular bursts can be due to the material influx into the inner disk because of the oscillations of the shock front far away from the compact object. The transition from the quiescent state to the burst state and vice versa is explained by the appearance and disappearance of the advective disk over its viscous time scale.

(iii) A series of X-ray soft-dips of durations in the range of 20–160 s were detected in the X-ray light curves during the transition of the source from a low-hard state to high-state in 1999 June observations. The transition takes place within a few hours as indicated by the RXTE/ASM and IXAE light curves (Naik et al. 2001). The lower panel in Figure. 3 shows a huge radio flare

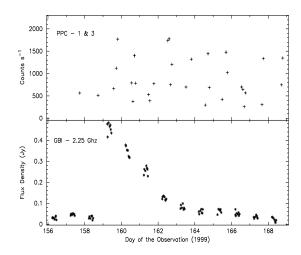


Fig. 3. The X-ray light curve for GRS 1915+105 with the PPCs (averaged over each orbit) in the energy range 2–18 keV and radio flux at 2.25 GHz with NSF-NRAO-NASA Green Bank Interferometer. The transition of the source from a low-hard state to a high-state was observed within a day as shown in top panel of the figure.

at 2.25 GHz which was observed with the NSF-NRAO-NASA Green Bank Interferometer following the change of state in X-rays as observed with the PPCs (upper panel). Detailed analysis showed that this huge radio flare was associated with the occurance of a series of X-ray soft dips as shown in Figure 4. During the the dips, the low frequency QPOs were absent and the spectrum was soft with less variability compared to the non-dip regions. In contrast to this, during the non-dip regions, the light curve of the source is dominated by a pronounced variability with the presence of low-frequency (~ 4 Hz) QPOs. The spectrum of the source is also hard during the non-dip regions. These X-ray dips are suggested as the cause of mass ejection due to evacuation of matter from the accretion disk producing a huge radio jet.

(iv) A change of state of the source from a high-state (consisting of regular and periodic bursts) to a low-state was observed during the 2000 June observations. the beginning of the observations, bursts with recurrence time of ~ 40 s were detected which changed to ~ 120 s towards the end of the observations. These regular and periodic bursts disappeared from the X-ray light curve within about 1.5 hours (one orbit of the satellite IRS-P3) and the source changed to a low-hard state as shown in the last panel of Figure 5. The spectrum of the source becomes harder as the burst proceeds and becomes hardest at the end of the decay. The bursts are marked by the presence of a secondary (tertiary) peak during their decay phase as seen in Figure 6. The secondary (tertiary) peak resolves gradually from the primary peak with the increase in the burst recurrence time and finally all the bursts disappear from the light curve when the state of the source is changed as shown in the last panel of Figure 6.

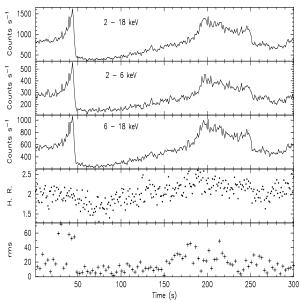


Fig. 4. Detailed light curves of GRS 1915+105 during an X-ray dip observed with the PPCs in 1999 June, with 1 s bin size in the energy range of 2-18 keV, 2-6 keV, and 6-18 keV. The dip is identical in shape in all the energy ranges. The hardness ratio (HR) is plotted in the fourth panel of the figure, which indicates the soft nature of the spectrum during the dips. The lower panel shows the variation in the rms of the source during the dip and non-dip regions.

4. DISCUSSION

Though the X-ray states of the microquasar GRS 1915+105 are classified into the canonical low-hard state and high-soft states as seen in other stellar black hole sources, it does exhibit extended low-hard states (Morgan et al. 1997). After the extended low-hard state, the source switches into a high-soft state which can be divided into different types, such as bright state, chaotic state and flaring state (Rao et al. 2000). The low-hard states are characterized by low frequency QPOs at ~ 2 - 3 Hz which according to the model of Molteni et al. (1996) is due to the oscillations of the shock. The QPO frequency varies inversely with the shock radius. Muno et al. (1999) found that the QPO frequency increases with the disk temperature and decreases with the disk radius. The regular and periodic bursts seen in the X-ray light curves are explained by the periodic infall of matter onto the black hole from an oscillating shock front (Molteni et al. 1996). According to this model, a shock is produced in the sub-Keplerian component of the accretion disk because of the centrifugal barrier. The shock starts oscillating if the cooling time of the post shock halo matches with the material infall time. The oscillation period depends on the angular momentum and the viscosity of the accreted matter from the companion star. If the accreted matter has high angular momentum and low viscosity, then the oscillation period is higher. They tried to explain all the observed properties of the bursts by the above model. The bursts result from a

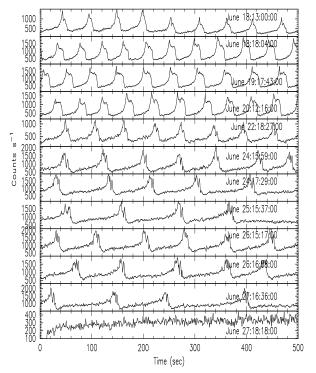


Fig. 5. The X-ray light curves for GRS 1915+105 with the PPCs in the energy range $2-18~\rm keV$ in 1 s time integration mode during the IXAE observation in 2000 June. Change in burst duration from 2000 June 18 to 27 is shown. The alphabets represent the data from different orbits of PPC observations.

catastrophic infall of matter, piled up behind the shock, onto the black hole which increases the temperature and hence the X-ray intensity. Paul et al. (1998b) and Yadav et al. (1999) have made a detailed study of such intensity variations using the data obtained with the IXAE. Yadav et al. (1999) concluded that the repeated intensity variation cannot be attributed to inner disk evacuation. This is due to the viscous time scale arguments as well due to the fact that the two intensity states are quite similar to the low-hard and high-soft state of the source. They invoked the two-component accretion-flow model (TCAF) of Chakrabarti & Titarchuk (1995) to conclude that the rapid changes are due to the appearance and disappearance of advective disk covering the standard thin disk without any requirements of mass ejection.

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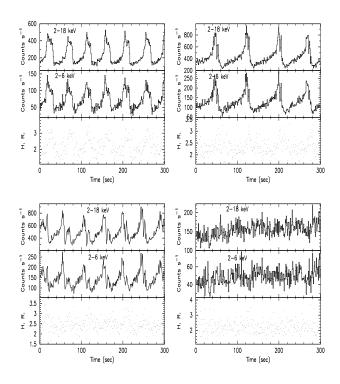


Fig. 6. The X-ray light curves of the source GRS 1915+105 obtained from IXAE during four different intervals of 2000 June observation are shown in the energy ranges $2-18~{\rm keV}$ and $2-6~{\rm keV}$ with hardness ratio (H. R. = Count rate in $6-18~{\rm keV}$ range/count rate in $2-6~{\rm keV}$ range). The appearance of secondary (and tertiary peaks) in the later light curves can be seen.

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